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# 6 DYNAMIC RESPONSE OF VERTEBRAL ELEMENTS RELATED TO USAF INJURY.

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by


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ABSTRACT

of

FINAL REPORT

for

DYNAMIC RESPONSE OF VERTEBRAL ELEMENTS RELATED TO USAF INJURY

(AFOSR Contract F 49620-77-C-0043)

Test specimens obtained from fresh-frozen Rhesus vertebral columns are used to determine that shear load distribution and stress-strain characteristics of the facets relative to the soft tissue. The specimens consist of two vertebrae and the intervening disc with the longitudinal ligaments intact.

Results of the initial tests show that at the onset of shear stress, the facets sustain from 60% to 80% of the load; with increasing shear force the fraction of the load carried by the disc and ligaments increases to 50-60%.

Failure of the facets resulted from bilateral fracture of the inferior facets at the margin. Without facets, failure typically occurs due to separation of the end plates from the vertebral body. The tests indicate that failure sequence progesses through (a) facet fracture, (b) end plate separation, and (c) tearing of ligaments.

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# DYNAMIC RESPONSE OF VERTEBRAL ELEMENTS RELATED TO USAF INJURY

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## A. INTRODUCTION

The key to the reduction in the number of spinal injuries resulting from ejection and ground landing forces lies in an integrated working knowledge of spinal mechanics and the dynamics of the support-restraint system (1). The establishment of a broad technical base for the design and development of future ejection seats and crew modules is the object of a systematic research program conducted by AMRL, AFOSR and their contractors. Contract F 49620-77-C-0043 is part of this program and is concerned with the stress-strain properties of the vertebra-disc complex under shear stress. The data obtained are required as input into the analytical models being developed to analyze the dynamic response of the man-machine system.

## B. RESEARCH PROGRAM

The initial investigations are designed to determine the stress-strain properties of the intervertebral disc and the load distribution (facets vs. disc) under shear stress. The protocol for determining load distribution is as follows:

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1. Kazarian, L., 1976 Review of Air Force Sponsored Research in Environmental and Acceleration Physiology, Write-Patterson AFB, Sept. 1976.

1. Two vertebrae and the intervening disc are submitted to shear loading (force normal to the spinal axis)

2. The shear force is increased at a constant rate until failure of the articulating facets

3. The force-deflection is recorded

4. Facets are completely removed

5. Shear force reapplied until failure of the disc

From the two force-deflection curves thus obtained the difference in the force for a given deflection is a measure of the portion of the shear force carried by the facets. The shear load distribution can, therefore, be determined for both components. Calculation of stress and strain is accomplished from measurement of the area of the intervertebral disc. The elastic modulus of disc-ligament components is obtained from the first derivative of the stress-strain curves.

These initial tests are conducted at low rates of loading to obtain the quasi-static properties of the material. Subsequent tests at high rates of loading are scheduled to provide the rate dependent characteristics.

## C. FACILITIES AND PROCEDURES

The experiments are designed to use spinal specimens from Rhesus monkeys. Each specimen consists of two vertebrae and the intervening disc with ligaments attached. The fresh, excised spines are fresh frozen at -20°C until preparation for testing. The spines are thawed six to eighteen hours before testing, excess soft tissue removed, and specimens separated. The specimens are stored in saline solution and refrigerated. Immediately prior to testing, a specimen is mounted on the test fixture and the test fixture positioned on the test stand.

The test facility is an electrohydraulic system assembled specifically for this project. The system, illustrated in Fig. 1, consists of the following com-

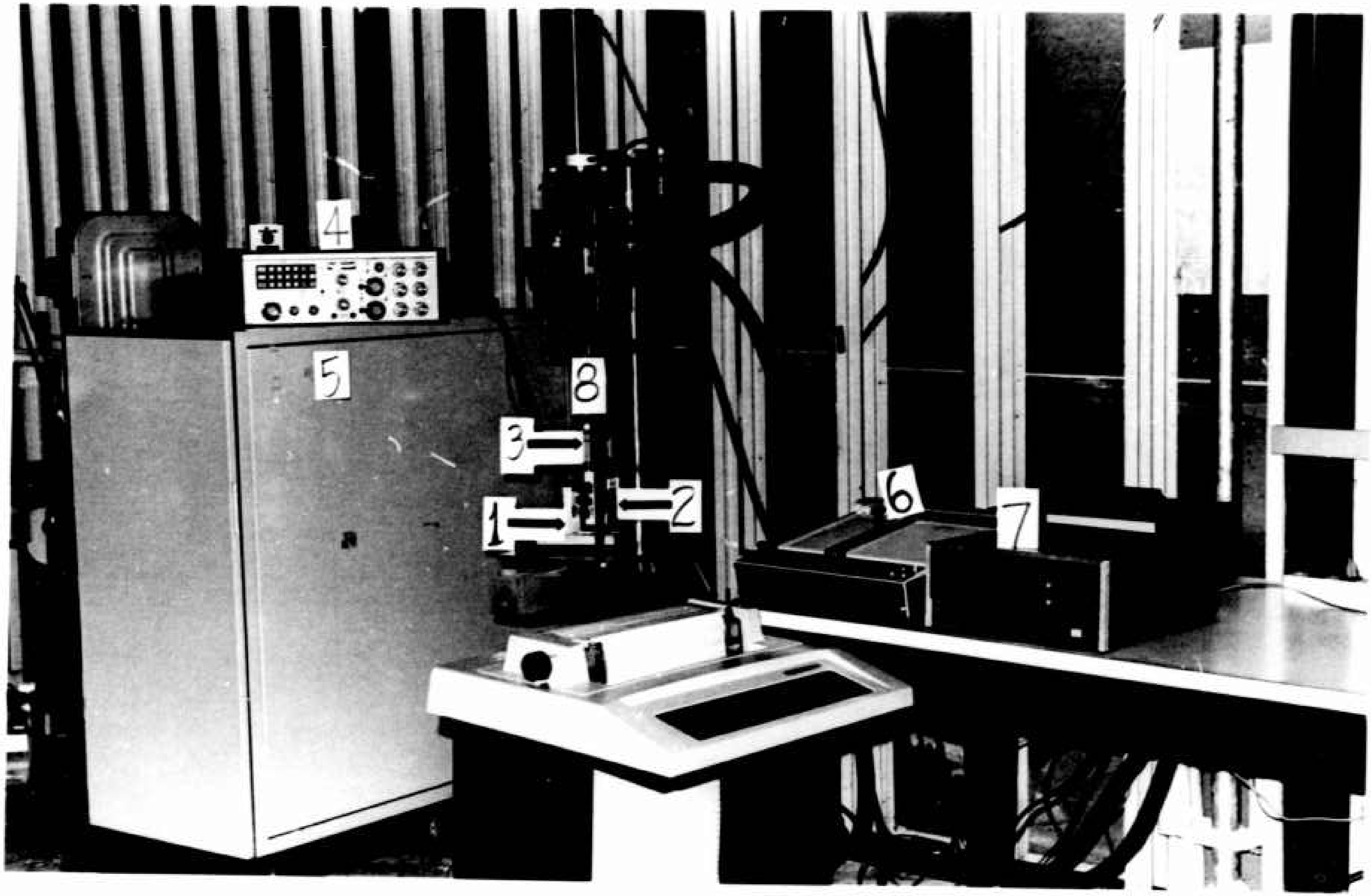


Fig. 1. Facility for Testing Spinal Specimens

ponents (with item numbers corresponding to those of Fig. 1):

1. Specimen holding fixture
2. Displacement transducer (Hewlett-Packard 24DCT)
3. Force transducer (Interface 500)
4. Feedback control system (MTS 442 Controller)
5. Hydraulic supply
6. Recorder (Hewlett-Packard 7004B X-Y)
7. Microprocessor controlled function generator and data acquisition system (SWTP 6800)

A flow graph of the system is shown in Fig. 2. The MTS Servoram Actuator and the MTS 442 Controller form a subsystem capable of providing a 2000 lb. (8900 N) load (tension or compression) over a six inch (15 cm) stroke. Either force or displacement can be fed back to the Controller as the control variable. A failsafe interlock feature in the Controller can stop the test whenever the interrupt flag is set. This flag can be set by any of the following conditions: (1) either force or displacement exceeding preset limit, (2) amplitudes of a cyclic force or displacement feedback signal falling below a preset level, or (3) excessive error (command signal-feedback signal) of the control variable.

The command signal to the controller is generated by the SWTP 6800 microprocessor and a digital to analog (D/A) converter. A command signal waveform is produced by scanning a block of memory which contains the waveform and outputting the data through a D/A converter to the controller. This "memory mapping" technique offers the flexibility of being able to select any of several different waveforms on a programmable time base, all of which is software controlled by the microprocessor.

The microprocessor also is capable of obtaining force and displacement feedback information through a multiplexed analog to digital (A/D) converter.

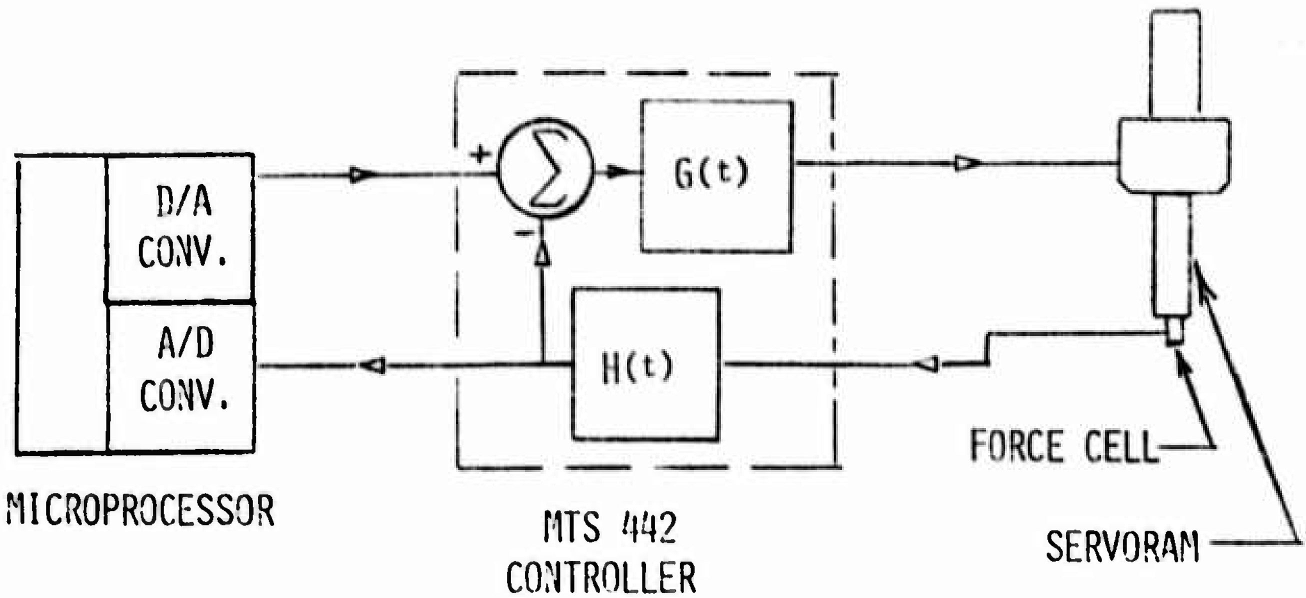


FIG. 2. FLOW GRAPH OF TEST SYSTEM

This allows the microprocessor to store the test data as well as monitor the test status and modify the control signal accordingly.

The present testing scheme uses force as the control variable. The microprocessor produces a command signal which increases linearly with time. The force on the specimen is sampled and stored in memory after each incremental increase of the command signal. The command signal increases at a selected rate to a preset level, then decreases at the same rate to a zero-force command. This sequence can be interrupted at any time by the activation of an emergency shutdown switch which causes the microprocessor to ramp the command signal back to a zero-force command.

The holding fixture, shown in detail in Fig. 3, is designed to accept lumbar and lower thoracic Rhesus vertebrae and, while holding the vertebral bodies rigidly clamped, submit the specimen to pure shearing stress in the A-P plane transverse to the spinal axis. This stress is resisted by the facets, disc, end plates (and their attachment to the vertebral bodies) and the ligamentous structure. With the inferior vertebral body held stationary, force is applied to the sliding half of the fixture which holds the superior vertebral body. Clamping of the vertebrae is facilitated by an adjustable pin which inserts into the neural canal, a clamp which straddles the spinous process and the use of epoxy to mate the contours of the vertebrae to the fixture surfaces. A typical mounting of a specimen is illustrated in Fig. 4.

The force applied is monitored by the load cell on the end of the hydraulic piston and in contact with the sliding element of the holding fixture. The relative displacement of the two vertebrae is monitored by the displacement transducer. The force is applied by the piston of the MTS Servoram system. Force feedback is used in these tests because the greater range of this variable permits more accurate control; displacement is, therefore, measured as the inde-

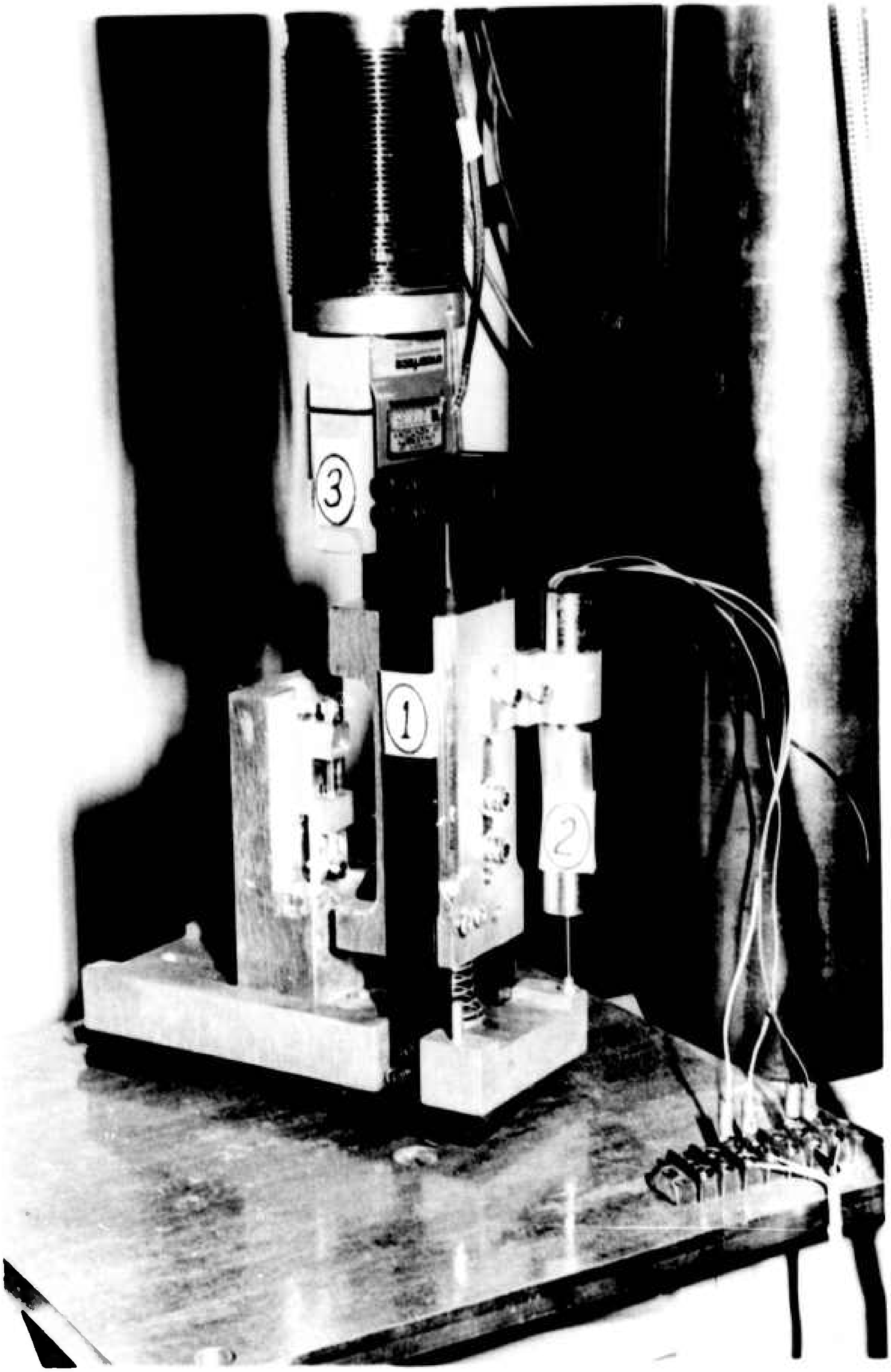


Fig. 3. Holding Fixture and Transducers

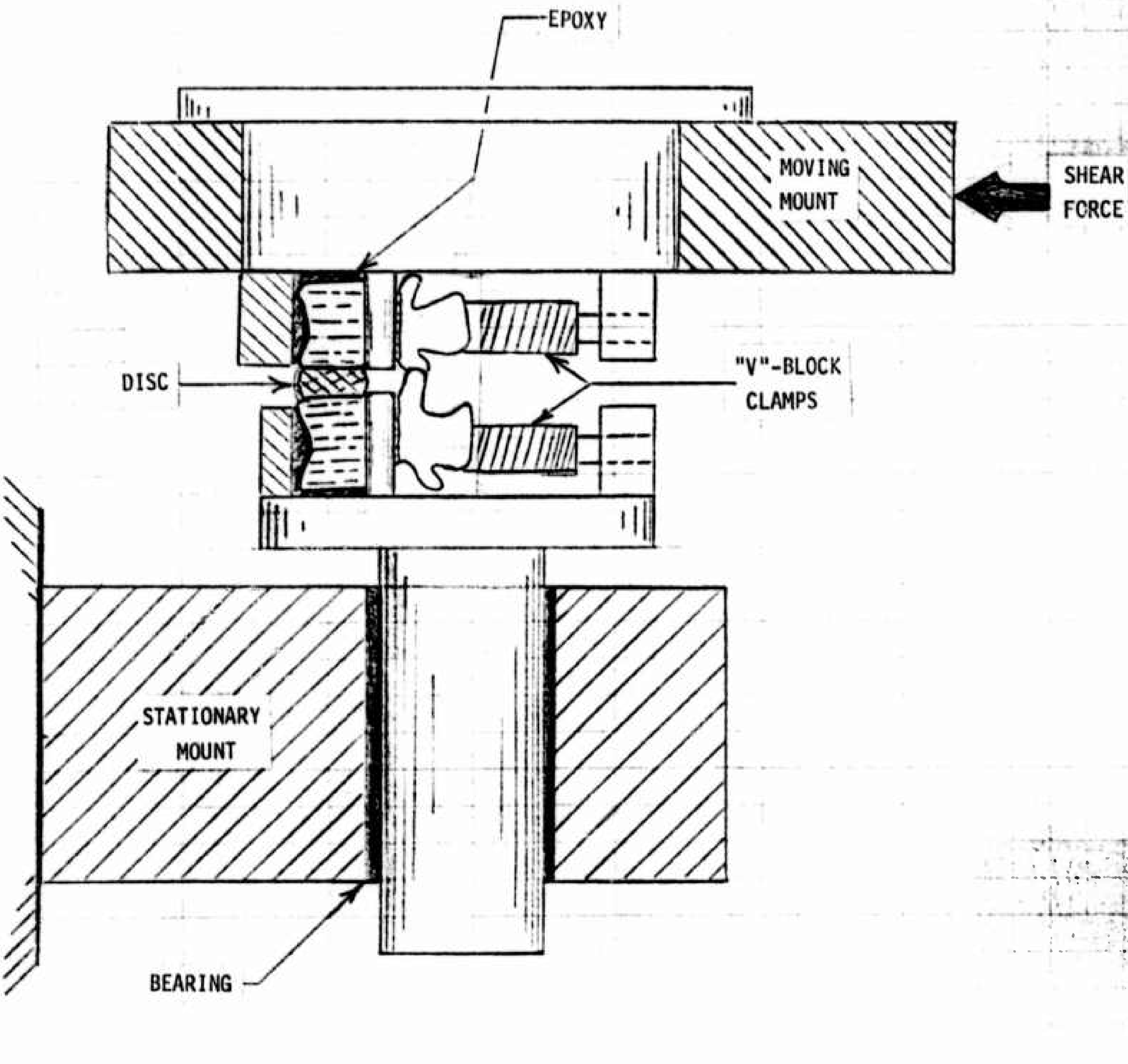


Fig. 4. Typical Specimen Mounting

pendent variable. The data (force vs. displacement) are recorded on a Hewlett-Packard X-Y recorder which, for the quasistatic test, provides excellent sensitivity and resolution. A Brush 2400 recorder, with a frequency response of 30 Hz at 100 mm amplitude has been obtained to record the data at loading rates which exceed the frequency response of the X-Y recorder. If necessary, a storage oscilloscope and galvonometer-type recorders are available for the high frequency data.

## D. RESULTS AND DISCUSSION

Preliminary data were obtained on several specimens to determine general response of the segments to shear stress, establish failure levels, specify recorder settings, test the holding fixture, and test the microprocessor programs for input signal and data acquisition. Inasmuch as these tests resulted in several modifications of the holding fixture and software for the microprocessor, the preliminary data obtained are not considered valid and are not included in the results presented in this report. The segments tested are tabulated in Table I by level, origin, and cause of death.

Typical specimen response is illustrated in Fig. 5 which presents the force-displacement characteristics of the specimens with and without facets. In both cases, failure occurs at approximately 840 N (189 lb.), with 3.5 mm displacement at facet failure and disc failure at 6 mm displacement. At facet failure, the disc carries about 75% (630 N) of the load which implies that the facets alone will fail at about 210 N (47 lb.).

Failure of the facets resulted from fracture of the inferior facets of the superior vertebra. Detailed examination of the fracture area is not possible in this series of tests since the facets are destroyed when removed. Disc failure typically occurred by separation of the end plate from the inferior surface of the superior vertebra as illustrated in the photograph of Fig. 6.

TABLE I

RHESUS TEST SPECIMENS

| SPINE NO. | SECTIONS | ORIGIN | CAUSE OF DEATH |
|---|---|---|---|
| 1 | T12-L1<br>L4-L5<br>L6-L7 | U.K. Medical Center | Strangulation |
| 2 | L1-L2<br>L3-L4<br>L5-L6 | U.K. Medical Center | Induced Coronary Occlusion |
| 3 | T12-L1<br>L2-L3<br>L4-L5<br>L7-S1 | U.K. Medical Center | Induced Coronary Occlusion |
| 4 | L2-L3<br>L4-L5<br>L6-L7 | U.K.--Dr. Olson | Peritonitis |
| 5 | L5-L6 | Delta Primate Research Center | |
| 6 | L1-L2<br>L3-L4<br>L5-L6<br>L7-S1 | Yerkes Primate Research Center | Enterocolitis (Shigellosis and Yersiniosis) |
| 7 | T12-L1<br>L2-L3<br>L4-L5 | Yerkes Primate Research Center | Endometriosis with Obstruction of Small Intestine |

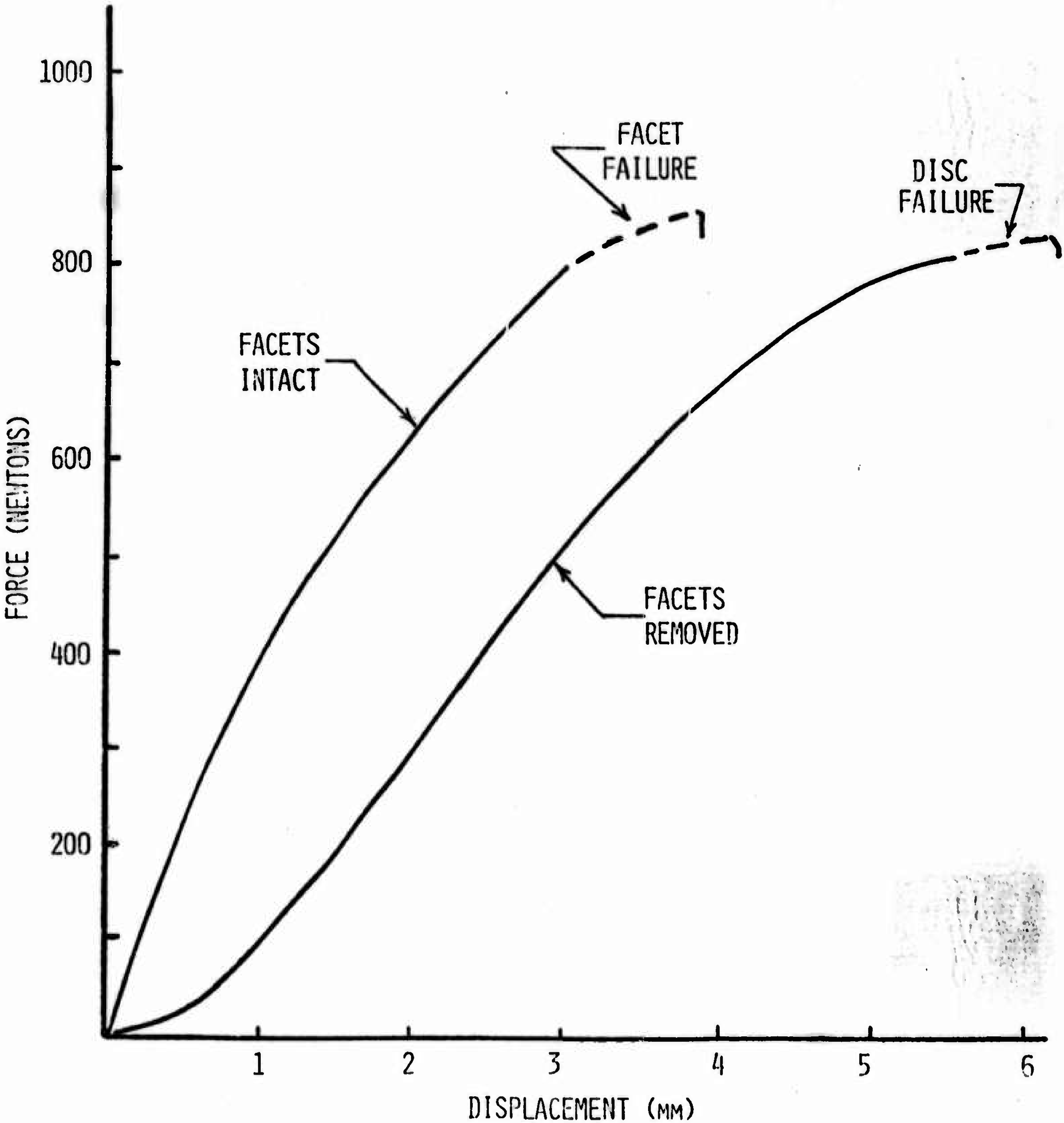


Fig. 5. Representive Force-Displacement Results


Fig. 6. Illustration of Failure by End Plate Separation

In this photograph, the superior vertebra is to the right and the inferior surface of the vertebral body is visible where the end plate has separated and the tissue torn. Normally the failure results with the disc unit (annulus, nucleus and end plates) left intact. In one case, however, extrusion of the nucleus through the annulus fibers was observed. This herniation was lateral and slightly anterior as shown in the photograph of Fig. 7. Generally, the data indicate that the failure sequence involves (1) facet fracture, (2) end plate separation, and (3) tearing of the ligaments.

From the original data (in the form of that in Fig. 5) the fraction of the total load carried by the soft tissue was computed (at a given displacement) and is displayed graphically in Fig. 8 as a function of total force applied. These results show that, on the average, the disc carries 50% to 60% of the load up to 400 N (90 lb.) and 3 mm displacement. Beyond this point, the facets fail at 3.5 to 4 mm displacement at which time the disc assumes 100% of the shear force and continues to yield until disc failure.

The shaded area in Fig. 8 represents the extent of the standard deviation (S.D.) from the mean. The magnitude of the S.D. reflects the fact that some of the specimens exhibited an unusually high stiffness (high elastic modulus). The stiffer specimens were from older subjects and most of the specimens in this group were from spine No. 7 (21-year-old female) which showed evidence of disc degeneration at all levels. The difference in these two groups is shown in Fig. 9 where "normal" designates the lower stiffness group which includes the majority of the data (9 specimens as compared to 5 specimens in the high modulus group). The data for the two groups are tabulated in Table II.

The stress-strain properties of the intervertebral discs were obtained from the force-deflection curves. The stress was based on the disc area which was obtained photographically. The strain was based on A-P dimension of the disc at

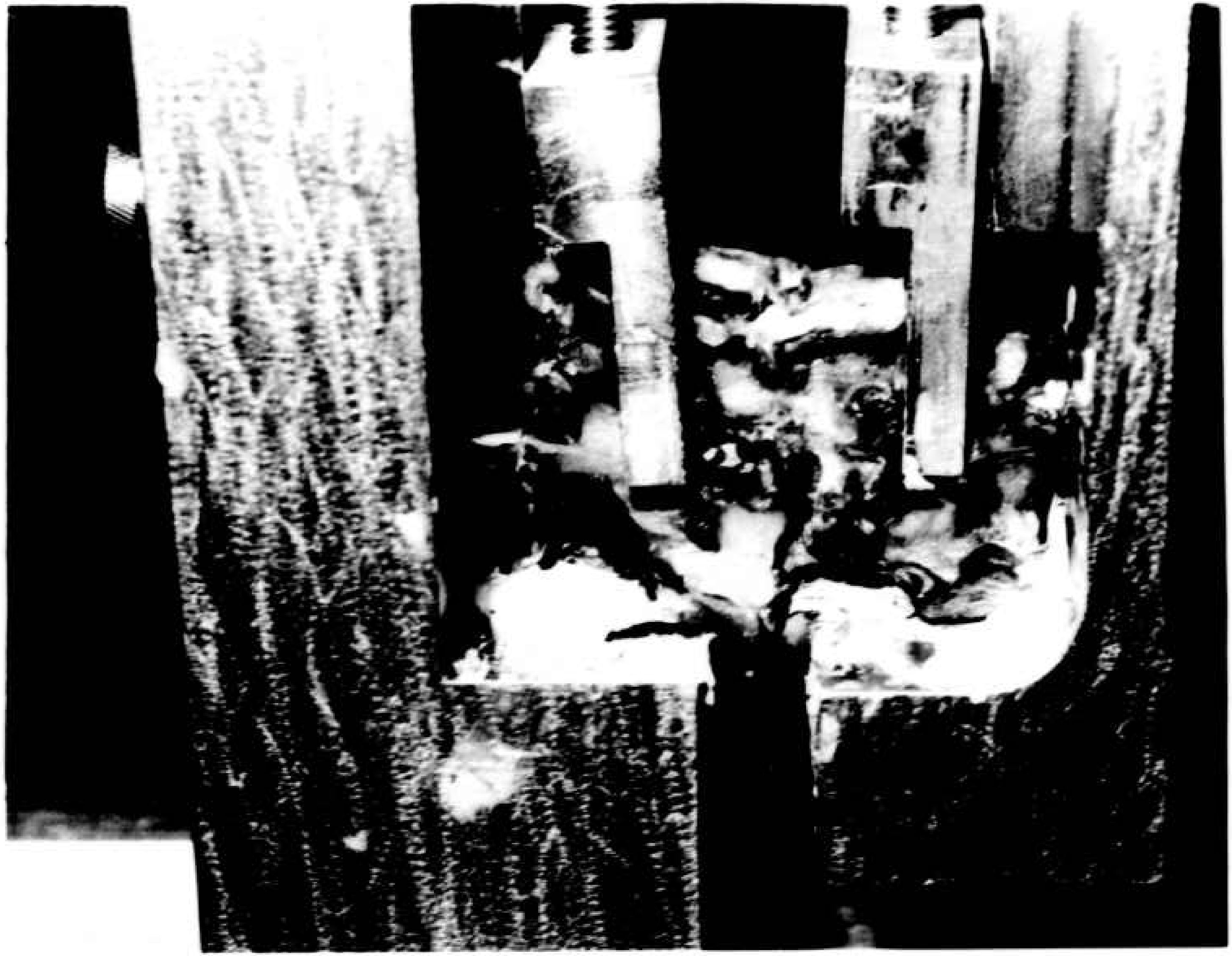

Fig. 7.  Illustration of Failure by Herniation of the Nucleus

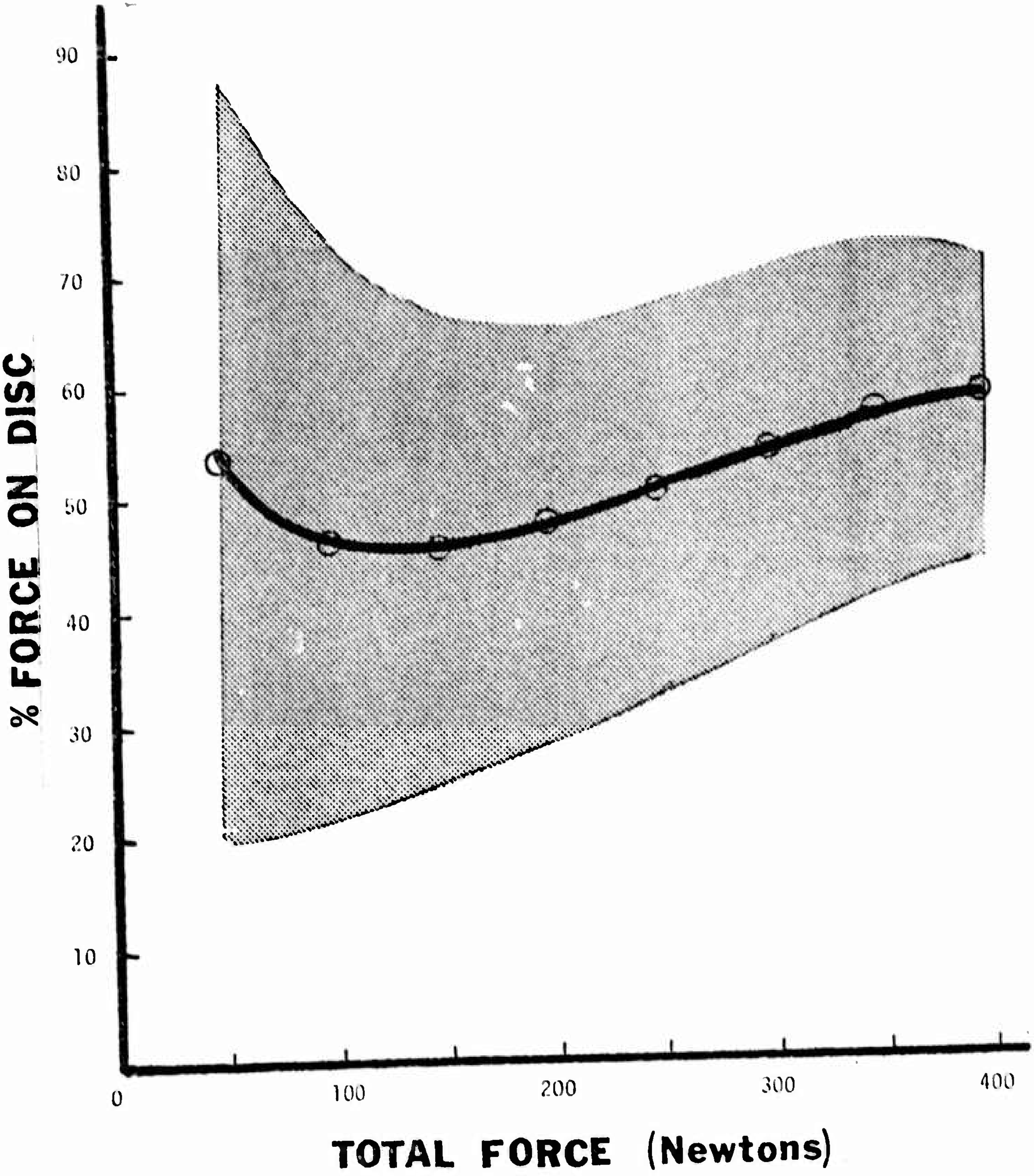


Fig. 8. Shear Force Carried By Disc as Percent of Total Force on Specimen. Shaded Area Represents Standard Deviation About the Mean.

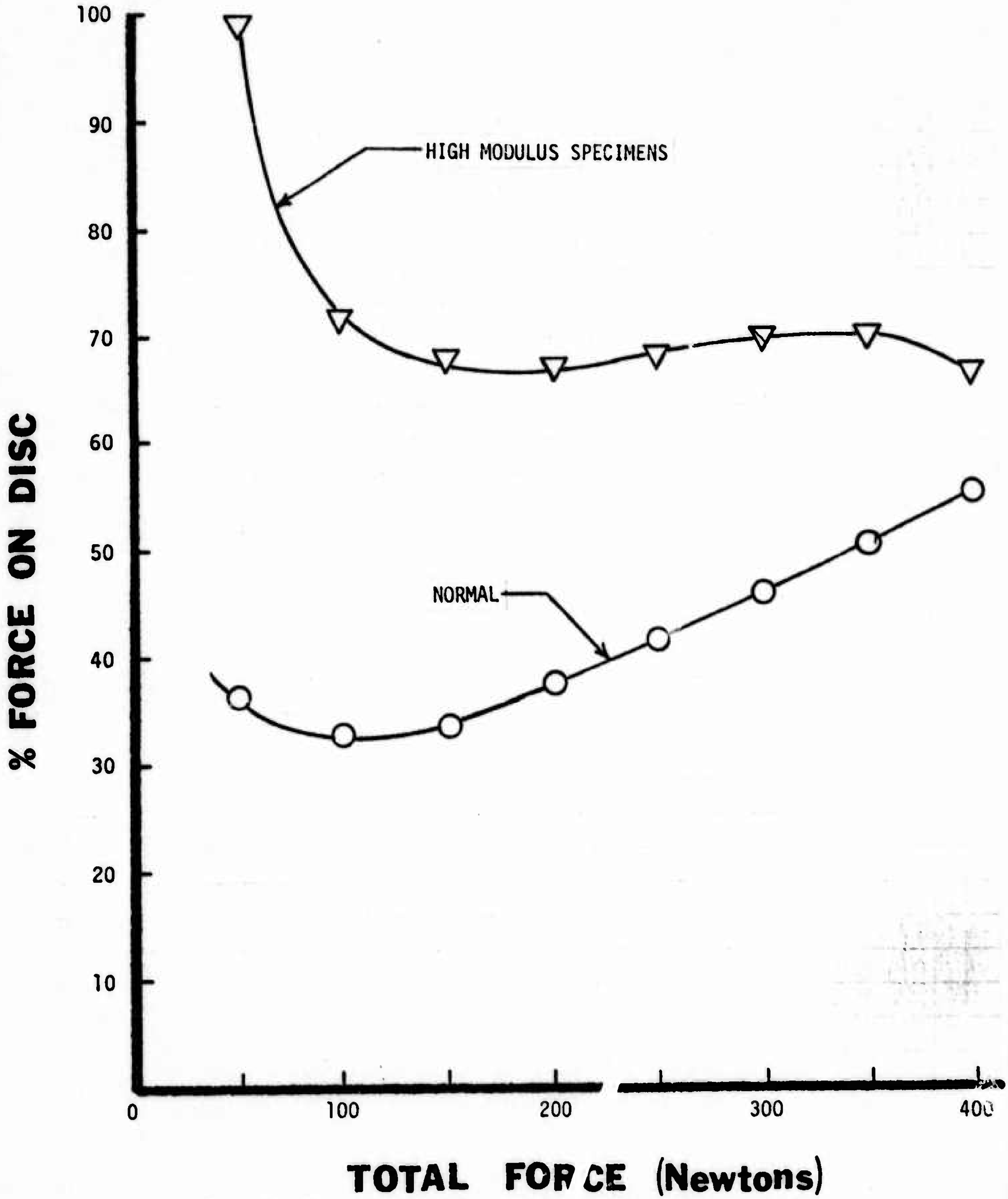


Fig. 9. Force Carried by the Di c. Data Separated into High Modulus and "Norm l" Groups.

TABLE II

FORCE DATA

| TOTAL FORCE (N) | DISK FORCE (% of TOTAL FORCE) (Mean Value ± S.D.) | NO. OF TESTS |
|---|---|---|
| | HIGH MODULUS GROUP | |
| 50 | 0.999 ± 0.356 | 3 |
| 100 | 0.712 ± 0.231 | 5 |
| 150 | 0.679 ± 0.199 | 5 |
| 200 | 0.669 ± 0.196 | 5 |
| 250 | 0.679 ± 0.191 | 5 |
| 300 | 0.696 ± 0.188 | 5 |
| 350 | 0.703 ± 0.191 | 5 |
| 400 | 0.666 ± 0.179 | 4 |
| | "NORMAL" GROUP | |
| 50 | 0.364 ± 0.104 | 8 |
| 100 | 0.326 ± 0.078 | 9 |
| 150 | 0.337 ± 0.082 | 9 |
| 200 | 0.375 ± 0.084 | 9 |
| 250 | 0.415 ± 0.088 | 9 |
| 300 | 0.460 ± 0.092 | 9 |
| 350 | 0.506 ± 0.098 | 9 |
| 400 | 0.551 ± 0.098 | 9 |

its midpoint. The average (± S.D.) for all specimens is shown in Fig. 10 and results in an elastic modulus E of 501.9 ± 10.91 N/cm$^2$ (728 psi). The results shown in Fig. 11 demonstrate the difference between the "normal" specimens and the high modulus group. The stiffer specimens exhibit an elastic modulus of 648.6 ± 14.1 N/cm$^2$ (941 psi) while the "normal" group has a modulus of 380.7 ± 8.4 N/cm$^2$ (552 psi).

Analysis of the data and histological examination of the specimens indicate that the difference in characteristics between high and low modulus specimens is a result of the origin of high modulus specimens from mature animals with evidence of disc degeneration. There is a possibility that friction in the stress fixture (which would indicate a higher stiffness) and slipping of the vertebrae in the fixture (which would indicate a lower stiffness) accounts for some of the variations observed. In order to evaluate the extent to which these potential artifacts may have affected the results, an improved mounting fixture has been designed and is in the process of fabrication. The new fixture utilizes ball bearings for all moving parts to insure that friction will be negligible at all force levels. The new fixture also provides improved clamping mechanisms to grip the vertebral bodies.

The next phase of the investigation will determine the stress-strain properties of the intervertebral disc at high strain rates (up to 350 mm/s). This work will be initiated as soon as the validity of the present data has been more firmly established.

In other studies conducted during this contract period, seven adult Rhesus monkeys have been subjected to implantations of calibrated stress fixtures made of surgical rubber tubing. The tubing has been applied like rubber bands between adjacent vertebrae, using the transverse processes as anchors. Stress levels have varied between 1.3 and 3.8 kg/cm$^2$ (based on measurement of the total

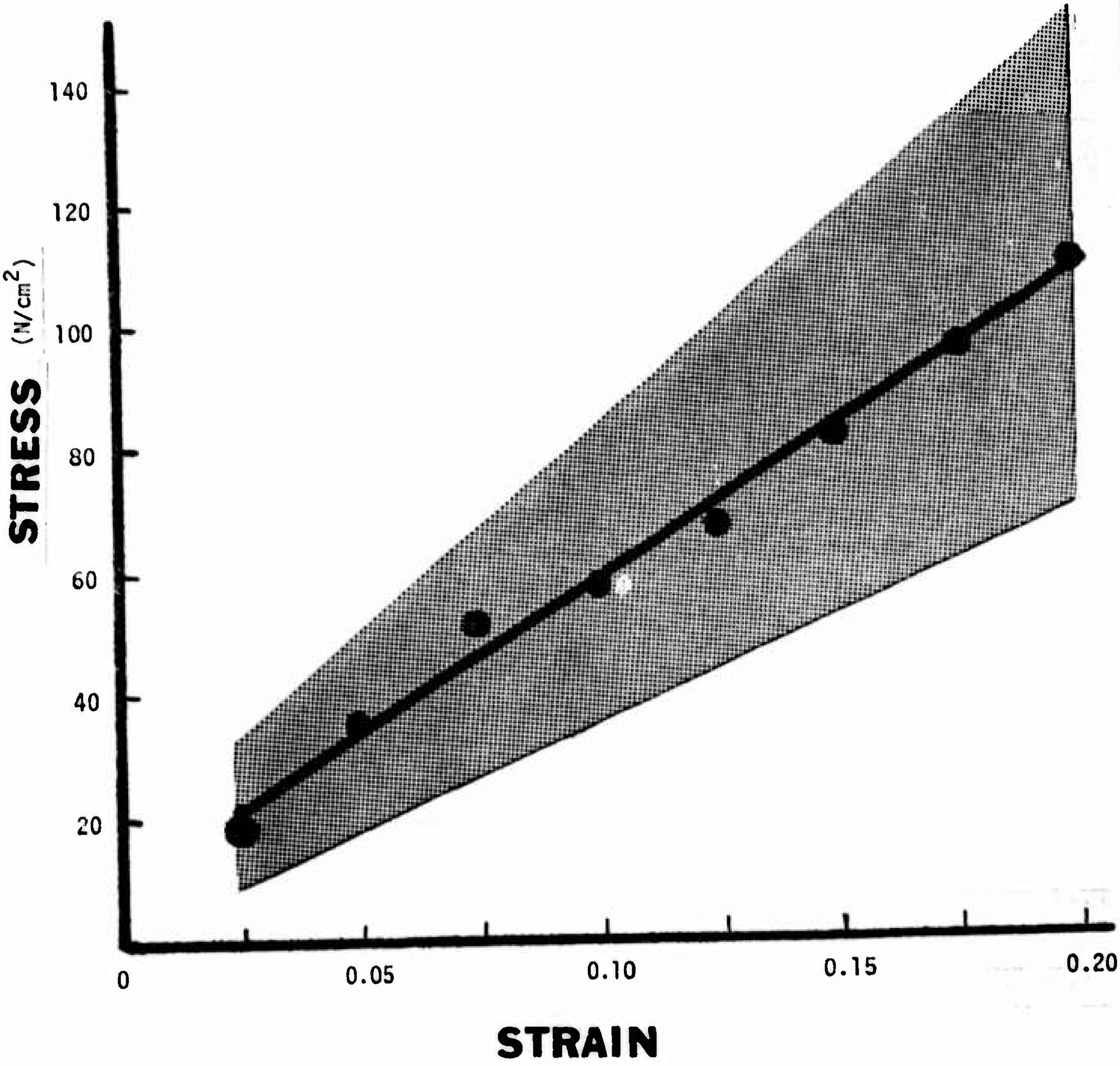


Fig. 10. Stress-Strain Curve for the Intervertebral Disc. Shaded Area Represents the Standard Deviation About the Mean.

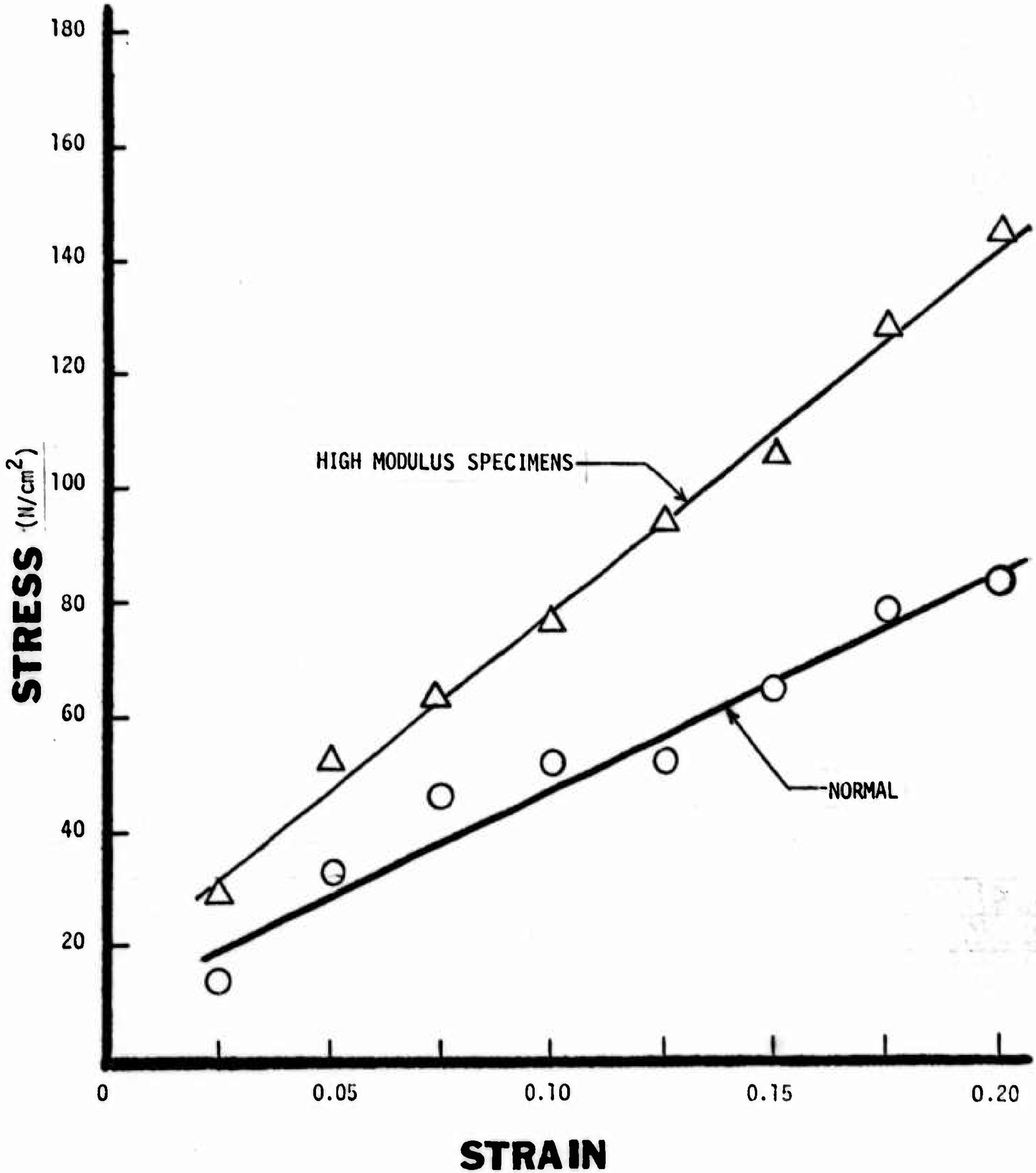


Fig. 11. Disc Stress-Strain Data Separated into High Modulus and "Normal" Groups.

TABLE III

STRESS-STRAIN DATA

| | HIGH MODULUS GROUP | |
|---|---|---|
| STRAIN (cm/cm) | DISK STRESS ($N/cm^2$) (Mean Value ± S.D.) | NO. OF TESTS |
| 0.025 | 13.95 ± 7.26 | 9 |
| 0.050 | 27.93 ± 13.51 | 9 |
| 0.075 | 46.29 ± 25.19 | 9 |
| 0.100 | 51.42 ± 22.94 | 7 |
| 0.125 | 51.98 ± 13.59 | 5 |
| 0.150 | 65.15 ± 18.15 | 5 |
| 0.175 | 78.92 ± 22.66 | 5 |
| 0.200 | 83.57 ± 21.38 | 4 |
| | "NORMAL" GROUP | |
| 0.025 | 28.53 ± 4.84 | 4 |
| 0.050 | 52.20 ± 6.92 | 4 |
| 0.075 | 63.34 ± 23.68 | 4 |
| 0.100 | 76.19 ± 26.82 | 3 |
| 0.125 | 94.05 ± 29.31 | 3 |
| 0.150 | 111.40 ± 31.39 | 3 |
| 0.175 | 128.74 ± 32.77 | 3 |
| 0.200 | 145.32 ± 34.25 | 3 |

cross-sectional area of the disc), and duration between 7 and 60 days. In one case, $C^{14}$ and $H^3$ labeled Mannitol was injected into the disc at the time of sacrifice to ascertain if there was any difference in the rate of diffusion out from normal and compressed discs. The use of $Na_2 S^{35}O_4$ has been initiated to determine diffusion into the disc from the general circulation. We have also developed a method for measuring the hydrostatic pressure within the nucleus pulposus using Dexon-filled 18 gauge hypodermic needles hydraulically coupled to a Millar pressure gauge. The following results have been obtained:

a. A reliable surgical implantation technique has been developed. The subjects fare well during and after the procedure.

b. The stress fixtures produce very little tissue reaction, being only thinly encapsulated by fibrous tissue.

c. The effective stress bearing area of the intervertebral discs of the Rhesus lumbar spine is initially approximately 1.6-2 $cm^2$. This figure is considerably smaller than the total area of the disc, indicating that at application, the annulus fibrosus and nucleus pulposus probably do not share the weight-bearing function equally. We are now in the process of determining the relative percentages of applied load being borne by both components.

d. The maximum stress we can apply without breaking the transverse processes in vitro results in a pressure of approximately 2 $kg/cm^2$ upon the effective area, and a hydrostatic pressure of approximately 1450 mm of mercury, or nearly 2 atmospheres above ambient in the nucleus pulposus. This pressure, as determined in bench tests, is maintained for only a very short period, dropping to about 1 $kg/cm^2$ above control values after 5 minutes, and remaining stable thereafter, for as long as we have continued the measurement. In vivo, after 60 days, pressure drops to control levels (80-100 mm Hg). This pressure, when applied for a period of 60 days, results in significant deterioration of the intervertebral disc.

e. The degeneration observed following compression of the disc is characterized by the following features:

1. Pyknosis of nucleus pulposus fibroblasts;

2. Loss of cells from and compression of the circular regions lying between the cartilage end plates and nucleus;

3. Altered staining and eventual loss of mucopolysaccharide matrix from both the hyaline cartilage end plates and fibrocartilage annulus; resulting in increased cell density;

4. Compression of chondrocyte lacunae in the end plates, and especially in the annulus;

5. Considerable loss of fluid from the nucleus pulposus with a resultant decrease in total disc height;

6. In cases where the stress has not been equal on both sides of the disc, the nucleus is forced to the low-pressure side, with consequent thinning of the annulus at that point;

7. Thinning of the hyaline end plates; microfractures and some reactive bone formation in the cortical bone end plates;

8. The compression does not appear to produce large changes in the rate of diffusion of labeled Mannitol out of the disc.

## SCIENTIFIC ARTICLES RESULTING FROM THIS RESEARCH PROJECT

1. IN PREPARATION

   "STRESS-STRAIN PROPERTIES OF THE LUMBAR INTREVERTEBRAL DISC". To be submitted to the ASME Journal of Biomechanical Engineering and for presentation at the 1978 ASME Winter Annual Meeting.

2. The following papers are peripheral to this project and AFOSR supported equipment was used in the research although no direct labor or materials used was funded under Contract F 49670-77-C-0043.

   "ANALYTICAL MODEL OF THE FATIGUE CHARACTERISTICS OF BONE", Lafferty, J. F., *Aviat. Space and Environ. Med.*, 49 (1): 170-174, 1978.

   "INFLUENCE OF STRESS FREQUENCY ON BONE FATIGUE". Submitted to *Jour. of Bone and Joint Surg.* January, 1978. To be presented to the 1978 meeting of the Orthopaedic Research Society, Dallas, Texas, February, 1978.

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